Comparison of Geostrophic Winds on constant pressure surfaces with observed winds in India

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ABSTRACT. The paper describes a method of comparing geostrophic winds derived from constant pressure surfaces with observed winds. The differences in heights of the constant pressure surfaces between five pairs of stations in India have been calculated using upper wind data for two levels, e.g., 850 mb and 700 mb. The differences have also been obtained from the data of radio-sonde ascents. These values have been compared and correlation coefficients have been worked out. Similar computations have been made for some cases in the British Isles. Some plausible explanations for the comparatively lower values of correlation coefficients for the Indian stations have been given.

1. Introduction.

The first attempt to compare winds derived from isobars with observed winds in India was by Ishaque. He compared the direction and velocity of the geostrophic winds derived from sea level isobars with the observed winds at different levels at Agra and Bangalore in the winter and hot weather periods. At Agra the gradient wind direction agreed very closely with the observed wind direction at 0.5 km. But the correlation between the computed velocity and the observed velocities at 0.5 and 1.0 km was very low, the correlation coefficients being respectively 0.34 and 0.39. At Bangalore the observed wind direction at all levels was very much at variance with that derived from the surface isobars. In the absence of upper air temperature data, Ishaque could not compare the observed winds at upper levels with the isobaric winds at the corresponding levels. Also, his study was confined to the winter and hot weather periods only.

Since 1944 daily upper air temperature and humidity data are available from a network of stations in India and neighbourhood and the contours of the constant pressure surfaces are being studied by forecasters in India. Hence it is of considerable interest to make a quantitative comparison of winds derived from the contours of the constant pressure surfaces and the observed winds.

The network of radio-sonde stations in India is not, however, close enough to construct the contours of the constant pressure surfaces unaided by observed winds. All that is possible is to draw the contours so as to fit the observed winds at pilot balloon stations and the height values (of the constant pressure surface) available for the radio-sonde stations. If this procedure is adopted, experience shows that there is generally no difficulty to fit the observed wind directions with the contour lines. But what is needed is a quantitative comparison between the contour and observed wind directions and velocities. In the present study a method has been evolved for such comparison on the assumption of geostrophic wind relation.

2. Method of comparison.

The geostrophic wind component \( n \), normal to the direction of \( \mathbf{u} \) on a constant pressure surface is given by

\[
\frac{dz}{dn} = -\frac{2\omega}{g} v \sin \phi \quad \ldots \quad (1)
\]

where \( \frac{dz}{dn} \) is the variation of the height of the constant pressure surface per unit distance in the direction \( \mathbf{n} \). \( \mathbf{v} \) is taken as positive when the wind is blowing towards the right hand side of an observer facing to increasing value of \( \mathbf{n} \).

If \( P \) and \( Q \) are any two points on the constant pressure surface,

\[
\int_{Q}^{P} \frac{dz}{Q} = -\frac{2\omega}{g} \int_{Q}^{P} v \sin \phi \ dn \quad \ldots \quad (2)
\]

The integral on the left hand side of the
The symbols $v_{AB}^{A}$ and $v_{AB}^{B}$ represent the wind velocities as measured at stations A and B normal to the line AB. PA, AB, BC and CQ are linear distances. $\phi_{1}$, $\phi_{2}$, $\phi_{3}$, and $\phi_{4}$ are the mean values of the latitude between P and A, A and B, B and C and C and Q.

The constant pressure surfaces studied are of 850 and 700 millibars. Strictly the upper winds used in computing $\Delta Z_{0}$ should be the wind at the level of the constant pressure surface. But since pilot balloon winds are computed for some fixed heights only, 5000 and 10,000 feet winds have been respectively used in computing $\Delta Z_{0}$ for the 850 and 700 mb surfaces. In the cases studied here, the lowest and the greatest heights attained by the 850 mb surface are 4428 and 5347 feet and by the 700 mb surface are 9914 and 11,400 feet. These are extreme values and generally the heights were nearer to 5000 and 10,000 feet.

3. Is the assumption of Geostrophic wind valid for low latitudes?

The method of comparison adopted here involves the assumption of geostrophic wind over Indian latitudes. It may be argued that the gradient wind equation should be used for these latitudes instead of the geostrophic wind equation. It is shown below that the assumption is as valid in the cases under study as in middle latitudes.

The equation for gradient wind is

$$2 \omega v \sin \phi + \frac{v^2}{r} = \frac{1}{\rho} \frac{\partial p}{\partial \phi} \ldots \ldots \ldots (4)$$

where $r$ is the radius of curvature of the path of the parcel of air. In deriving geostrophic wind $v_{z}$ is neglected in comparison to $2 \omega v \sin \phi$ and hence the geostrophic wind equation is valid whenever $v^2/2 \omega v \sin \phi$ or $v/2 \omega r \sin \phi$ is small. It has been verified by various workers that the geostrophic wind is very highly valid in middle latitudes. Hence if the factor $v/2 \omega r \sin \phi$ is of the same magnitude in Indian and middle latitudes, geostrophic wind should be theoretically as much valid in India as in middle latitudes. Let the suffixes 1 and 2 respectively represent...
conditions in middle latitudes and India. Then for our assumption to be valid

\[
\frac{v_2}{2\omega_2 \sin \phi_2} = \frac{v_1}{2\omega_1 \sin \phi_1} \\
\text{or} \quad \frac{v_2}{r_2 \sin \phi_2} = \frac{v_1}{r_1 \sin \phi_1}
\]

Leaving aside tropical cyclones, there is no reason to think that on the average \( r_2 \) is less than \( r_1 \). Hence we regard \( r_2 = r_1 \). So the condition reduces to

\[
\frac{v_2}{\sin \phi_2} = \frac{v_1}{\sin \phi_1}
\]

It will be seen in the results presented here that comparison between calculated and observed values of \( \Delta z \) has also been carried out for some cases in Great Britain and the correlation coefficient is about 0.9 for these cases. The mean value of \( \sqrt{\theta \sin \phi} \) for the cases in Great Britain and India under study here are given in the table of results. It will be seen that \( \sqrt{\theta \sin \phi} \) is of the same order in Indian cases as in those from Great Britain. Hence it appears that the cyclostrophic component may be neglected in India with as much justification as in Great Britain. The Indian cases under study are limited to the north of 18°N latitude.

4. Results.

\( \Delta z \) has been computed and compared with observations for the following pairs of radio-sonde stations—(1) Delhi-Nagpur (2) Delhi-Allahabad (3) Allahabad-Calcutta (4) Karachi-Veraval (5) Veraval-Poona. Comparison is made separately for the four periods, December to March, April and May, June to September, and October and November to bring out any seasonal peculiarities.

The pilot balloon stations used in computing \( \Delta z \) are shown in Fig. 2. Only such cases as when pilot balloon winds are available at all the pilot balloon stations between the two radio-sonde stations have been used for comparison.

In order to see the validity of the method adopted here, similar comparison has been made between (1) Stornoway and Aldergrove and (2) Aldergrove-Valentia, stations in Great Britain for one month January 1948. The location of these stations and pilot balloon stations made use of, are represented in Fig. 3. The pilot balloon winds
used are nearest in time to the time of radio-
sonde ascents, if they are not synchronous
with the radio-sonde ascents.

Correlation coefficients have been calcula-
ted between $\Delta Z_e$ and $\Delta Z_0$ in all cases and
the results are given in Tables 1 to 7. The
times of radio-sonde ascents and the times of
pilot balloon ascents are given in the
tables. In the cases of Stornoway-Aldergrove,
Aldergrove-Valencia and Delhi-Nagpur (May
and June 1948) both the radio-sonde and pilot
balloon ascents are of the same time and
strictly comparable. In all other cases the
radio-sonde ascents are made 3½ hours later
than the pilot balloon ascents. It is assumed
in all these cases that the pilot balloon data
collected 3½ hours earlier are also valid at
the times of radio-sonde ascents.

In the four cases from Great Britain stu-
died, the correlation coefficients are between
0.86 and 0.93 which represent a very high
correlation. The number of observations
in each case are few only (24 to 26) but the
uniformly high correlation leaves no doubt
as to the relationship and the correctness of
the method of comparison adopted here.
The difference between the mean values of
$\Delta Z_e$ and $\Delta Z_0$ is also very small, the
maximum difference being only 10%.

From the tables the following features
will be noticed about the Indian data:

(i) The correlation coefficients vary be-
tween the wide limits of 0.62 and 0.96, some
cases in Table 2 giving even small negative
coefficients.

(ii) Between the same two stations, the
correlation coefficients vary widely during the
different months of the year. The only excep-
tion is between Veraval and Poona where the
correlation coefficients are consistent and of
moderate value.

(iii) The pilbar data are of ascents made
3½ hours earlier than the radio-sonde ascents.
Opportunity was taken to compare $\Delta Z_e$ and
$\Delta Z_0$ between Delhi and Nagpur for May-
June 1948 when radio-sonde and pilbar data
were available for the same time, viz. 0700
hours I.S.T. It will be seen in Table 1 that
this case gives a much lower correlation
coefficient than the evening data.

(iv) Mean values of $\Delta Z_e$ (without refer-
tence to sign) are smaller for Indian data than for
British data. This is to be expected on
account of the weaker winds over the
subtropics compared to the middle latitudes.

(v) In most of the cases for the Indian
stations (except Delhi-Nagpur) the mean
values and standard deviations (without taking
sign) of $\Delta Z_e$ are very much greater than the
mean values of $\Delta Z_0$. Even with Poona-Veraval
where the correlation coefficients are
consistent and of moderate value, $\Delta Z_e$ is
generally much greater than $\Delta Z_0$ which makes
the significance of the correlation coefficient
in this case doubtful. For example with an
average of 117 observations in case of 700 mb
surface mean $\Delta Z_e$ between Poona and Veraval
is 88 feet while the $\Delta Z_0$ is only 25 feet. It is
also seen that the standard deviations of
$\Delta Z_e$ (taking into account sign) are mostly
much more than that of $\Delta Z_0$.

5. Effect of errors of observation on the
correlation coefficients.

Both $\Delta Z_e$ and $\Delta Z_0$ must be subject to
errors of measurement. Hence a discussion
is given below how errors of measurement
will affect the correlation coefficients.

Let $x$ and $y$ denote the departures from
the mean of the true values (without errors of observation) of two quantities,

\[ x = \bar{x} + e \]  \hspace{1cm} (5)

\[ y = \bar{y} + f \]  \hspace{1cm} (6)

and $e$ and $f$ the errors of observation
respectively, referred to above.

It may be assumed that the errors are not
correlated either with values of observations
or among themselves. For the sake of sim-
plicity, the departures from the mean have
been considered instead of the actual values.

Obvious

\[ x = x + a \]  \hspace{1cm} (7)

\[ y = y + b \]  \hspace{1cm} (8)

Using the standard symbols $r$ for the correlation
coefficient and $\sigma$ for the standard deviation

\[ r = \frac{\sum xy}{\sigma_x \sigma_y} \]  \hspace{1cm} (9)

and

\[ r_{xy} = \frac{\sum xy}{\sigma_x \sigma_y} \]  \hspace{1cm} (10)

\[ r_{xy} = \frac{\sum (x + a) (y + b)}{\sigma_x \sigma_y} \]  \hspace{1cm} (11)

\[ r_{xy} = \frac{\sum xy}{\sigma_x \sigma_y} \]  \hspace{1cm} (12)

\[ r_{xy} = \frac{\sum (x + a) (y + b)}{\sigma_x \sigma_y} \]  \hspace{1cm} (13)
Now \[ \Sigma(x+a)(y+b) = \Sigma xy + \Sigma x + \Sigma y + \Sigma ab \]
\[ = \Sigma xy \quad \ldots \quad (10) \]
since the errors are not correlated with the observations and among themselves and the three terms \( \Sigma x, \Sigma y, \) and \( \Sigma ab \) vanish.

Also
\[ n \sigma_{x}^2 = \Sigma x^2 + n \sigma_{x}^2 \]
\[ = n(\sigma_{x}^2 + \sigma_{y}^2) \]
or
\[ \sigma_{x}^2 = \sigma_{x}^2 - \sigma_{y}^2 \quad \ldots \quad (11) \]
Similarly
\[ \sigma_{y}^2 = \sigma_{y}^2 - \sigma_{x}^2 \quad \ldots \quad (12) \]

Substituting the above values in equation (9) we have
\[ \frac{r_{xy}}{r_{xy}} = \frac{\sigma_{x} \cdot \sigma_{y}}{\sigma_{x} \cdot \sigma_{y}} \]
\[ = \left\{ 1 - \left( \frac{\sigma_{x}}{\sigma_{y}} \right)^2 \right\} \cdot \left\{ 1 - \left( \frac{\sigma_{y}}{\sigma_{x}} \right)^2 \right\} \]
\[ = \left\{ 1 - \frac{\sigma_{x}}{\sigma_{y}} \right\} \cdot \left\{ 1 - \frac{\sigma_{y}}{\sigma_{x}} \right\} \]
\[ = \left\{ 1 - \frac{\sigma_{x}}{\sigma_{y}} \right\} \cdot \left\{ 1 - \frac{\sigma_{y}}{\sigma_{x}} \right\} \]
\[ \frac{r_{xy}}{r_{xy}} = (0.75) \frac{\sigma_{x} \cdot \sigma_{y}}{\sigma_{x} \cdot \sigma_{y}} \]
\[ = 0.87 \left\{ 1 - \frac{\sigma_{x} \cdot \sigma_{y}}{\sigma_{x} \cdot \sigma_{y}} \right\} \]
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6. Explanation for the low correlation observed.

The standard deviations of \( \Delta Z \), and \( \Delta Z \), (taking into account the sign of the values) are given in the tables. These correspond respectively to \( \sigma_{x} \) and \( \sigma_{y} \). The mean error \( \sigma_{x} \) (corresponding to \( \Delta Z \)) computations of \( \Delta Z \), round the closed circuit Delhi, Gwalior, Allahabad, Bareilly and Delhi have been made. \( \Delta Z \), should be zero if the wind is geostrophic. Corresponding to 60 cases in November and December 1949, at the 5000 feet level for 0700 hours 18.37' pibal ascents, the mean value of \( \Delta Z \), is zero with a standard deviation of 16 feet. The deviation of \( \Delta Z \), from zero round a closed circuit would be the effect of the deviation of the wind from geostrophic assumption and errors in measurement of pilot balloon winds. This standard deviation \( \sigma_{x} \), will increase with the length of the circuit. The closed circuit Delhi-Gwalior-Allahabad-Bareilly-Delhi is longer than any of the routes for which \( \Delta Z \), and \( \Delta Z \), are correlated. So 16 feet may be taken as the \( \sigma_{x} \) for \( \Delta Z \),.

If \( \sigma_{x} = 2\sigma_{a} \), equation (13) becomes
\[ \frac{r_{xy}}{r_{xy}} = (0.75) \frac{\sigma_{x} \cdot \sigma_{y}}{\sigma_{x} \cdot \sigma_{y}} \]
\[ = 0.87 \left\{ 1 - \frac{\sigma_{x}}{\sigma_{y}} \right\} \cdot \left\{ 1 - \frac{\sigma_{y}}{\sigma_{x}} \right\} \]

Whenever the standard deviation of \( \Delta Z \), is more than 32, we should expect \( r_{xy} \) to be (0.87 \( r_{xy} \)) or more if there were no errors in \( \Delta Z \),. But it will be seen that there are many cases of very poor correlation even when the standard deviation of \( \Delta Z \), is more than 32 feet.

Two alternatives are open to explain the poor correlation between \( \Delta Z \), and \( \Delta Z \),.

(i) The error in measurement of \( \Delta Z \), is large. The fact that the mean value of \( \Delta Z \), and its standard deviation (neglecting the signs) are greater than the corresponding values of \( \Delta Z \), lends support to this view. The degree of accuracy that is required in the heights of constant pressure surfaces can be derived from the mean values of \( \Delta Z \), (neglecting sign). The lowest values of mean \( \Delta Z \), for any pair of stations in any season out of the cases studied here is 15 feet for 850 mb surface. In order that the heights of constant pressure surfaces may be capable of quantitative interpretation, the probable error in height measurement must be less than the mean value of \( \Delta Z \), indicated before. In the case of 850 mb surface, it is equivalent to an accuracy of 1 C in temperature measurements and still greater accuracy, in the case of 700 mb surface, assuming that errors are only in temperature measurements. Owing to the very much weaker winds in sub-tropics, the accuracy required in height measurements for constant pressure surface is much greater than in the middle latitudes.

(ii) Deviations from geostrophic wind in our latitudes are large. Geostrophic wind neglects the cyclostrophic and tangential acceleration. From a comparison of the values of \( v \sin \phi \), it was shown before that the cyclostrophic acceleration may be neglected here with as much justification as in higher latitudes. So the deviations must be chiefly due to the tangential acceleration.

7. Acknowledgment.

The work was undertaken at the suggestion of Sri V. P. Rao, whose guidance, counsel and encouragement were invaluable. I wish to record here my most sincere thanks to him. I would also like to express my sincere thanks to Dr. S. Mull, who took lively interest in the work.

REFERENCE.

### TABLE 1. (R.S* DELHI-NAGPUR.)

<table>
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<tr>
<th>Period</th>
<th>Time of ascension</th>
<th>R.S. P.B. IST</th>
<th>18T</th>
<th>No. of Obs.</th>
<th>Mean value $\Delta Z_e$</th>
<th>Standard Deviation $\Delta Z_o$</th>
<th>Correlation coefficient</th>
<th>Mean value (omitting signs) $\Delta Z_e$</th>
<th>Standard Deviation (omitting signs) $\Delta Z_o$</th>
<th>$r$ $\sin \phi$</th>
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<td>-30</td>
<td>-11</td>
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<td>57</td>
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<td>44</td>
<td>48</td>
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<td>73</td>
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<td>Oct-Nov 1947</td>
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<td>71</td>
<td>62</td>
<td>40 41</td>
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</table>

### TABLE 2. (R.S: DELHI-ALLAHABAD)

| Dec-Mar 1945-1946 | 1930 1600 | 91  | -14 | +12 | 29 | 33 | 0.11 | 24 | 47 | 21 | 38 | 27.1 |
| Apr-May 1946      | " 1500   | 23  | -3  | -36 | 36 | 119| -0.07| 27 | 62 | 24 | 105| 24.0 |
| June-Sept 1946    | " 1500   | 31  | +14 | +36 | 27 | 62 | 0.57 | 26 | 51 | 17 | 33  | 26.2 |
| Oct 1946          | " 1500   | 17  | +7  | -2  | 17 | 92 | -0.10 | 17 | 71 | 8  | 38  | 21.6 |

### TABLE 3. (R:S: ALLAHABAD-CALCUTTA)

| Jan-Mar 1946      | 1930 1600 | 49  | +1  | -32 | 35 | 118| 0.86 | 28 | 103| 21 | 68 | 33.6 |
| Apr & May 1946    | " 1500   | 17  | +10 | -120| 17 | 64 | 0.96 | 15 | 121| 13 | 61 | 24.3 |

### Notes:
- R.S. = Radio Sonde Stations.
- P.B = Pilot Balloon Stations.
Jan. 1951] GEOSTROPHIC AND OBSERVED WINDS IN INDIA

<table>
<thead>
<tr>
<th>Period</th>
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<th>R.S. IST</th>
<th>P.B. IST</th>
<th>No. of Obs.</th>
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<th>Standard Deviation $\Delta Z_e$</th>
<th>Correlation coefficient $\rho_e$</th>
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**TABLE 4.** (R.S. KARACHI-VERAVEL) (P.B. Karachi-Bhuj-Veraval)

(a) $850 \text{ mb.}$

(b) $700 \text{ mb.}$

**TABLE 5.** (R.S. VERAVAL-POONA) (P.B. Veraval-Bombay-Poona)

(a) $850 \text{ mb.}$

(b) $700 \text{ mb.}$

**TABLE 6.** (R.S. STORNOWAY-ALDERGROVE) (P.B. Stornaway-Aldergrove)

(a) $800 \text{ mb.}$

(b) $700 \text{ mb.}$

**TABLE 7.** (R.S. ALDERGROVE-VALENTIA) (P.B. Aldergrove-Valentia)

(a) $800 \text{ mb.}$

(b) $700 \text{ mb.}$

*Observed winds at 6000' were made use of for calculating values of $\Delta Z_e$. 